2015 International Workshop
on EUV and Soft X-Ray Sources

Water-Window Microscope Based on Nitrogen Plasma Capillary Discharge Source

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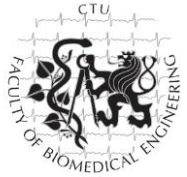
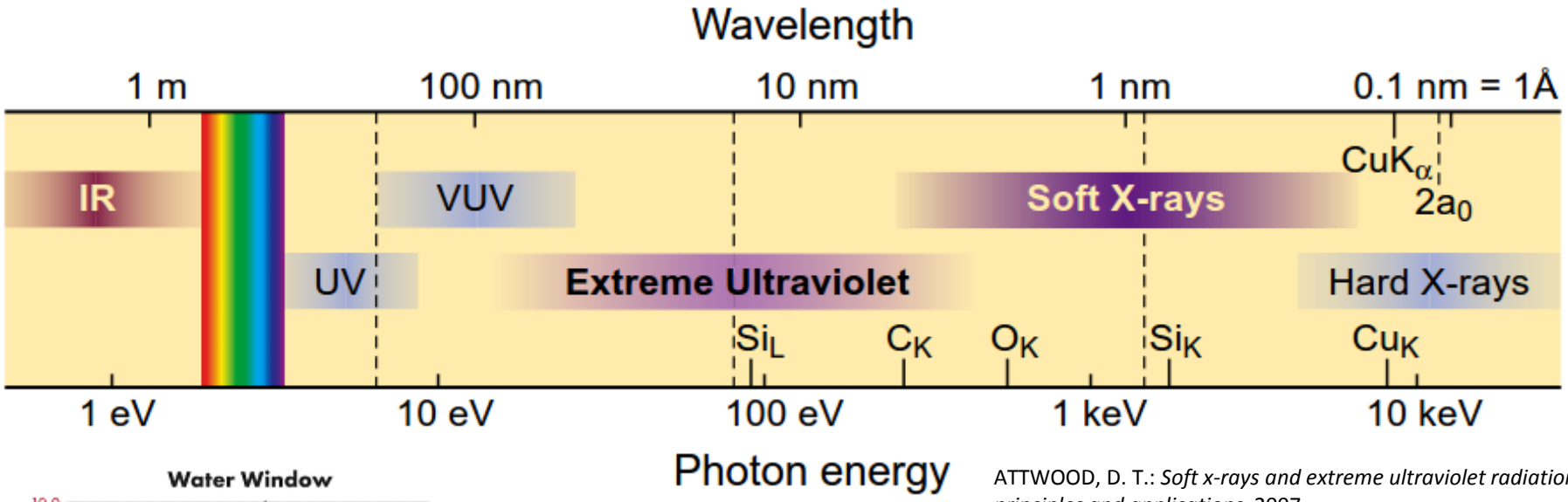


George Moore Auditorium, UCD Campus
Dublin, Ireland
November 9-11, 2015

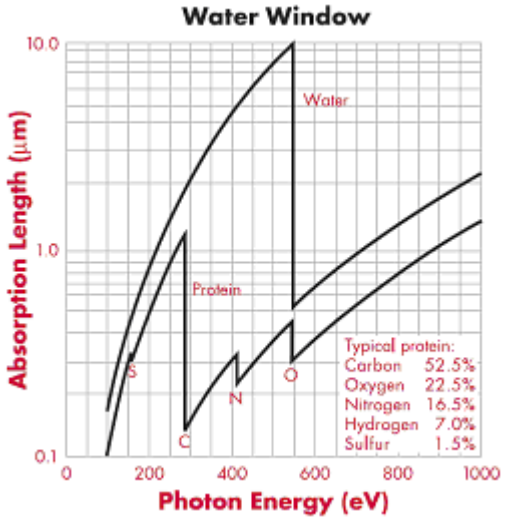
Outline

- Motivation
- Capillary discharge source
  - Characterization and description
- Water-window microscope based on nitrogen plasma capillary discharge and its optics
- Initial results
- Summary and outlook

Motivation – soft x-ray microscopy

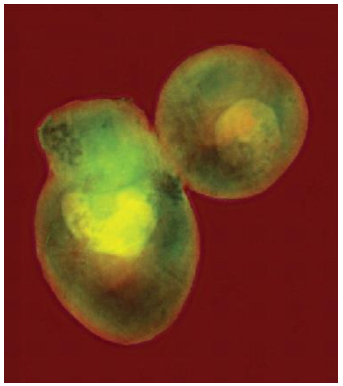


ATTWOOD, D. T.: *Soft x-rays and extreme ultraviolet radiation: principles and applications*. 2007

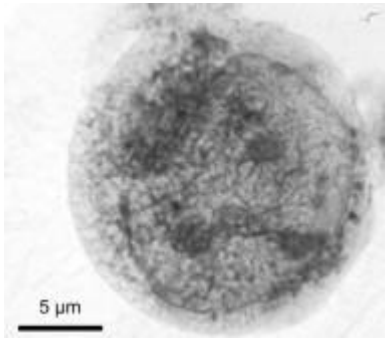


Princeton Instruments: X-Ray Applications

- Water window 2.3 – 4.4 nm (540 – 280 eV)

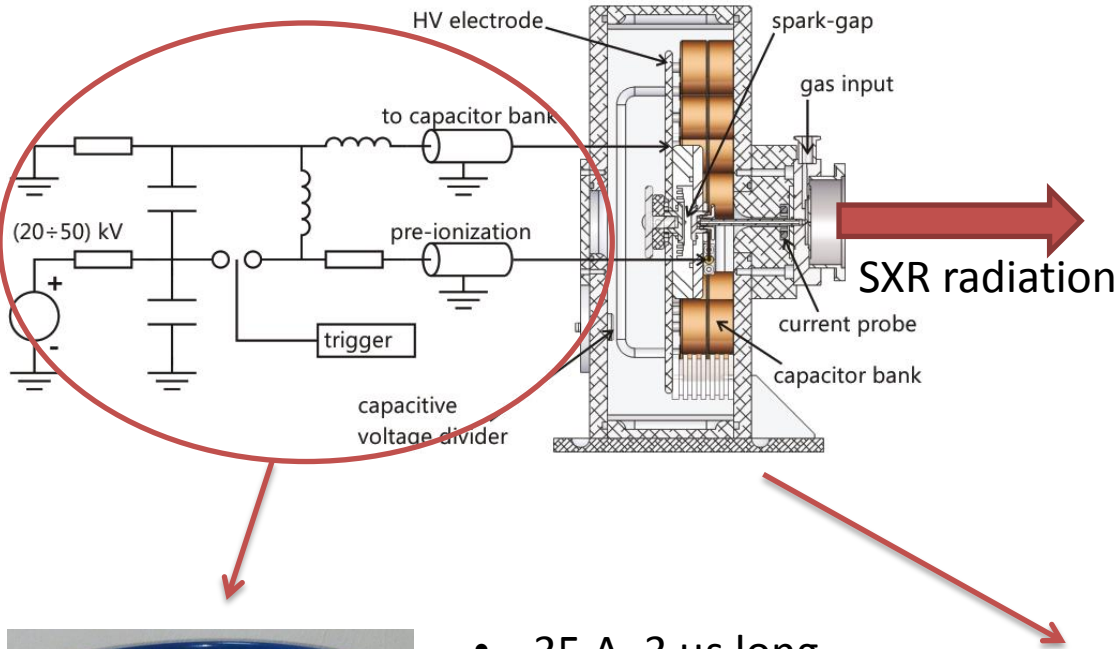


Berkeley Lab., 2010



H.M. Hertz et al. / Journal of Structural Biology 177 (2012)

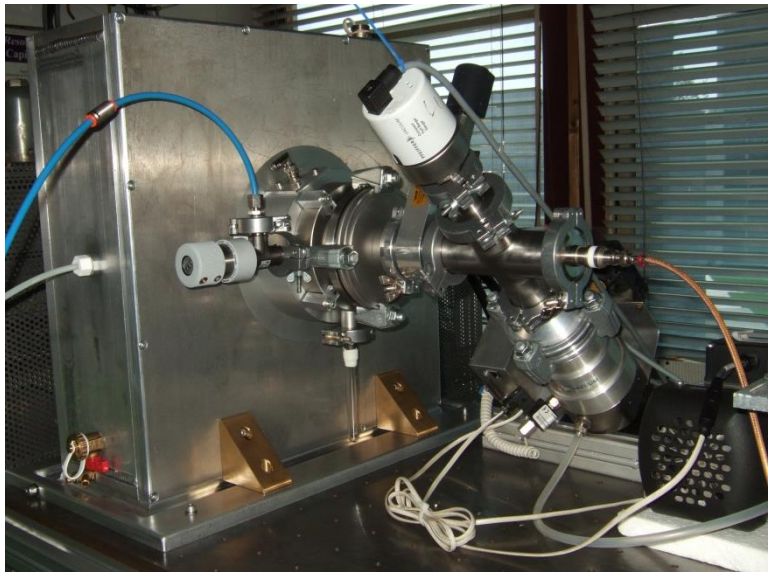
Discharge produced plasma as a source of soft x-ray



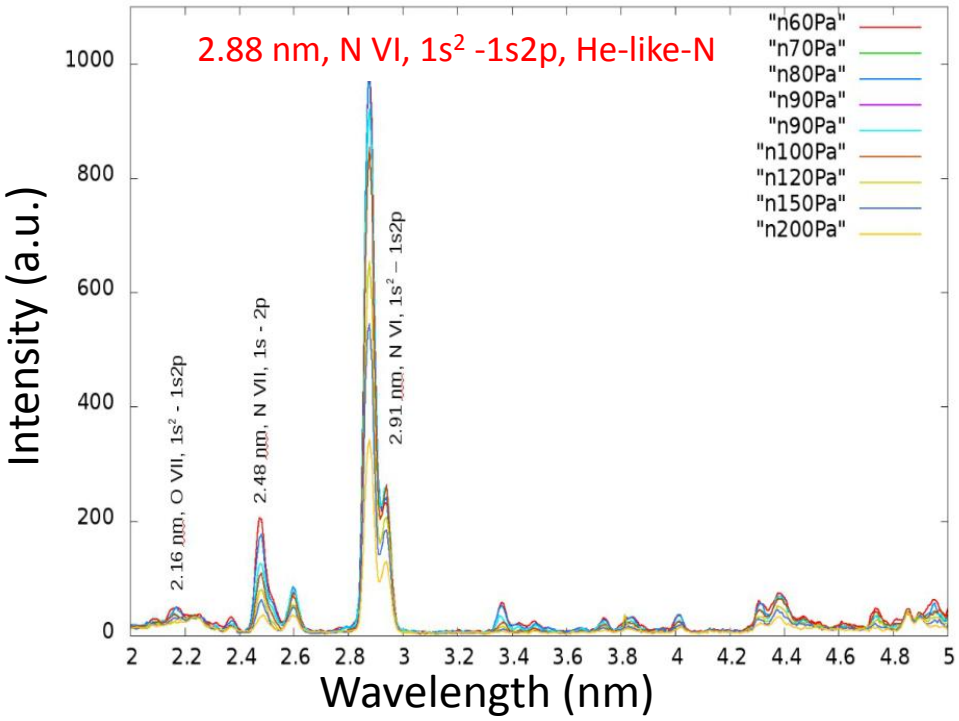
Alumina capillary (Al_2O_3)	
Length (cm)	10
Inner diameter (mm)	3.2

Plasma driver parameters	
Ceramic capacitor bank (nF)	21
Generator (kV) (maximum)	100
Maximum current (kA)	31
Inductance (nH)	50

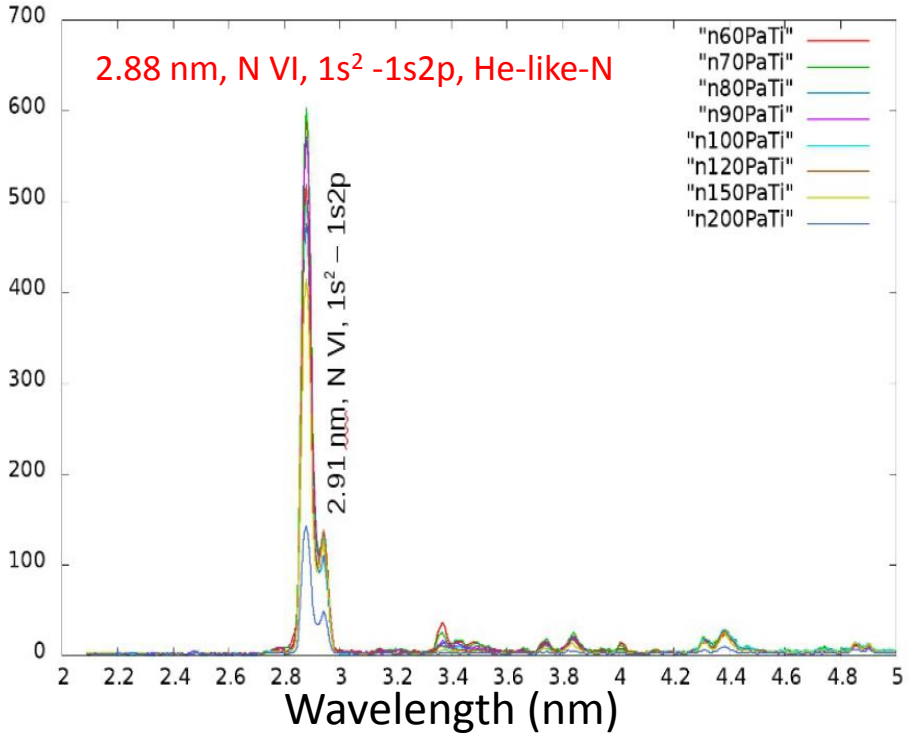
- 35 A, 3 μs long current pulse pre-ionizes the gas in the capillary
- Main current has damped sinus shape, with half-period of 150 ns and maximum amplitude of ~31 kA



Nitrogen spectra measurement in water-window region

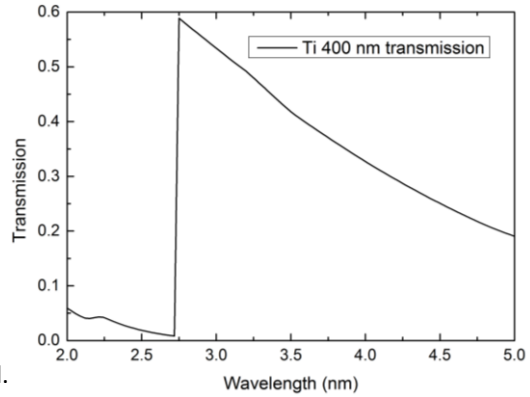


Nitrogen spectra without Ti filter



Nitrogen spectra with Ti filter

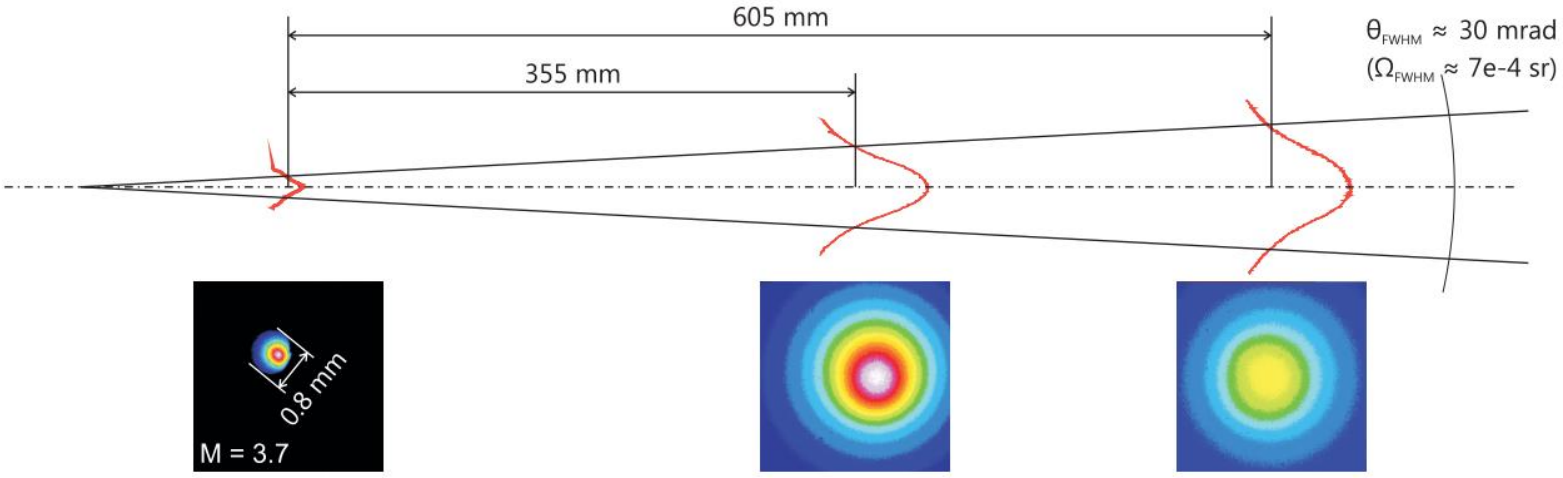
- Spectroscopic system has resolution of 0.03 nm
- BI-CCD camera with 512 x 512 pixels was used
- Silicon nitride diffraction grating with 100 nm period was used



J. Novak et al.: Measurement of spectra in “water window” wavelength region, Source Workshop 2012, Dublin

The center for X-ray optics, Henke B.L. et al.

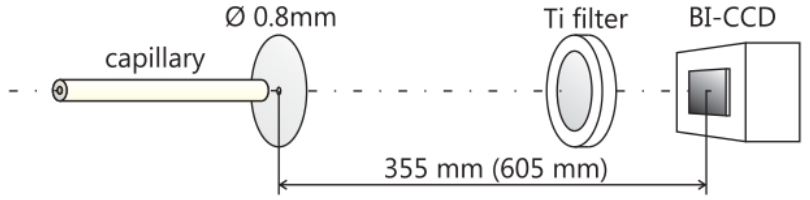
Discharge produce plasma characterization



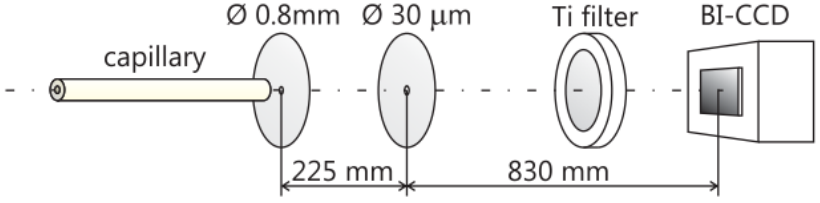
FWHM ~0.3 mm | FWHM ~12 mm | FWHM ~18 mm

DPP characterization	
System size	2 m^2
Filling gas	Nitrogen
Photon flux per sr per pulse	5.5 x 10^{13} photons
Energy/(pulse per sr)	3.8 mJ
Source efficiency	4.5 x 10^{-5}
Peak power per sr	87 kW
Beam divergence (FWHM)	30 mrad
Source size (FWHM)	360 µm

T. Parkman et al.: Comparison of Laser Produced Plasma and Discharge Produced Plasma as a Source for SXR Microscopy, Source Workshop 2014, Dublin



Layout for beam profile measurement

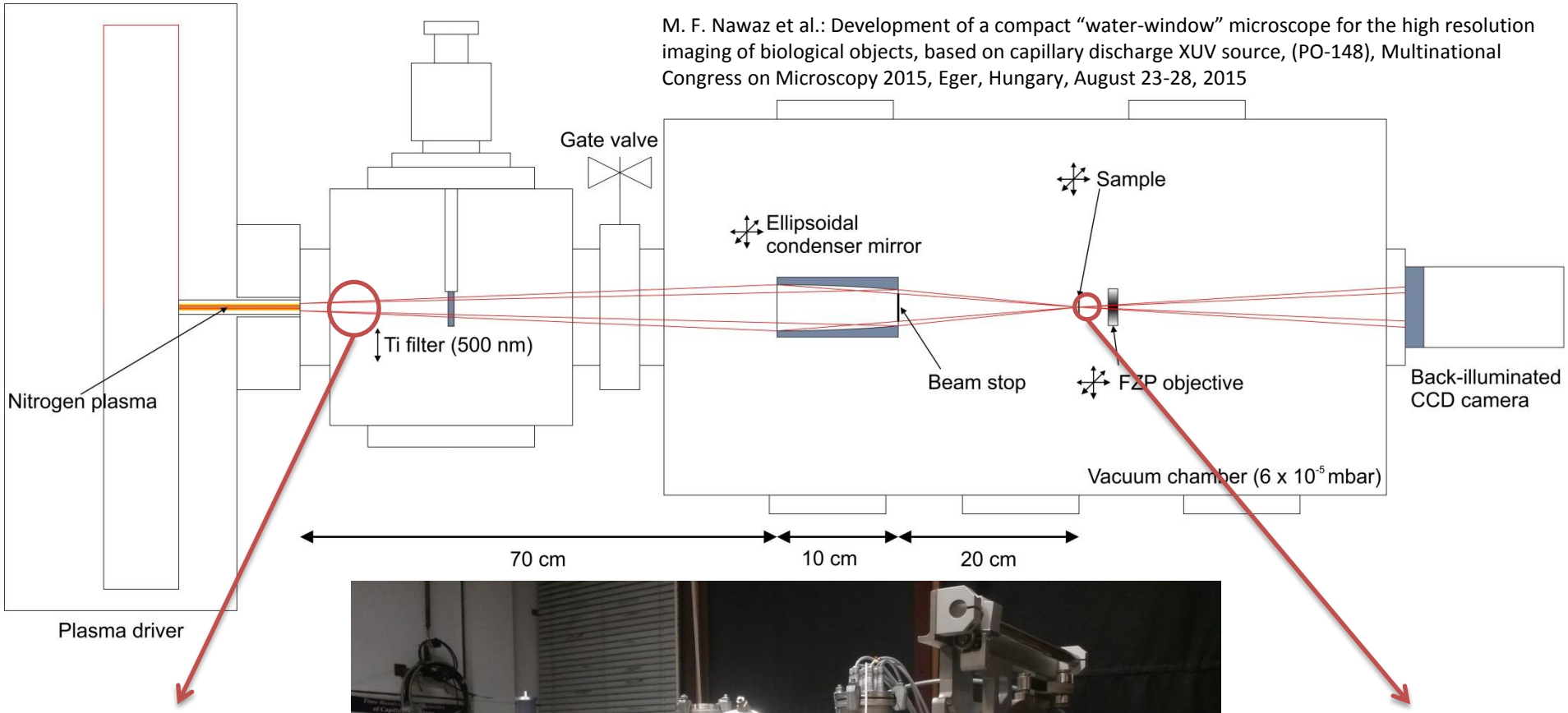


Layout for source size measurement

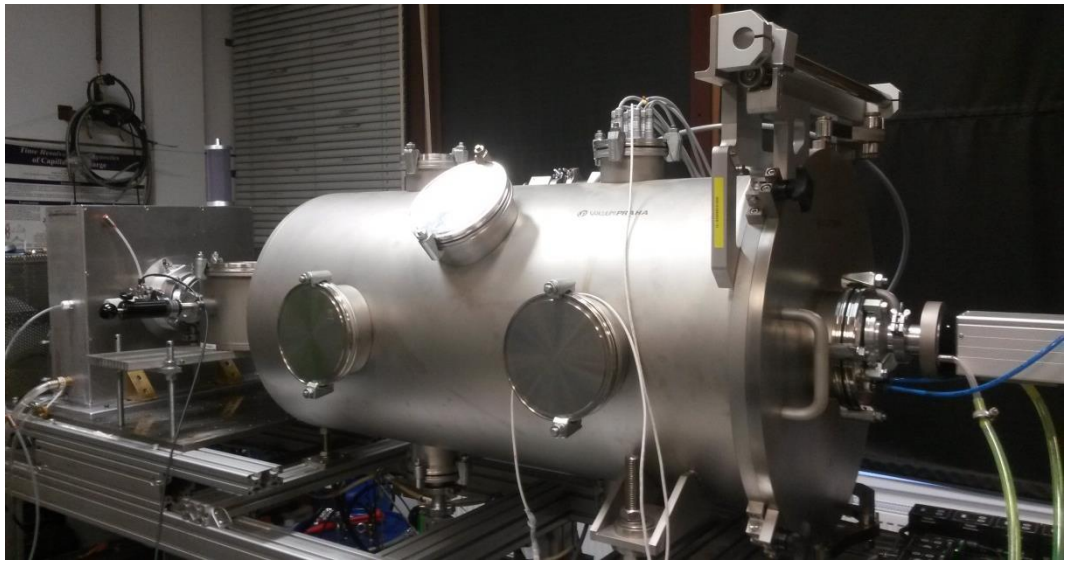
M. Nevrkla et al.: Characterization of capillary discharge water-window radiation source, Source Workshop 2012, Dublin

Water-window microscope based on capillary discharge source

M. F. Nawaz et al.: Development of a compact “water-window” microscope for the high resolution imaging of biological objects, based on capillary discharge XUV source, (PO-148), Multinational Congress on Microscopy 2015, Eger, Hungary, August 23-28, 2015

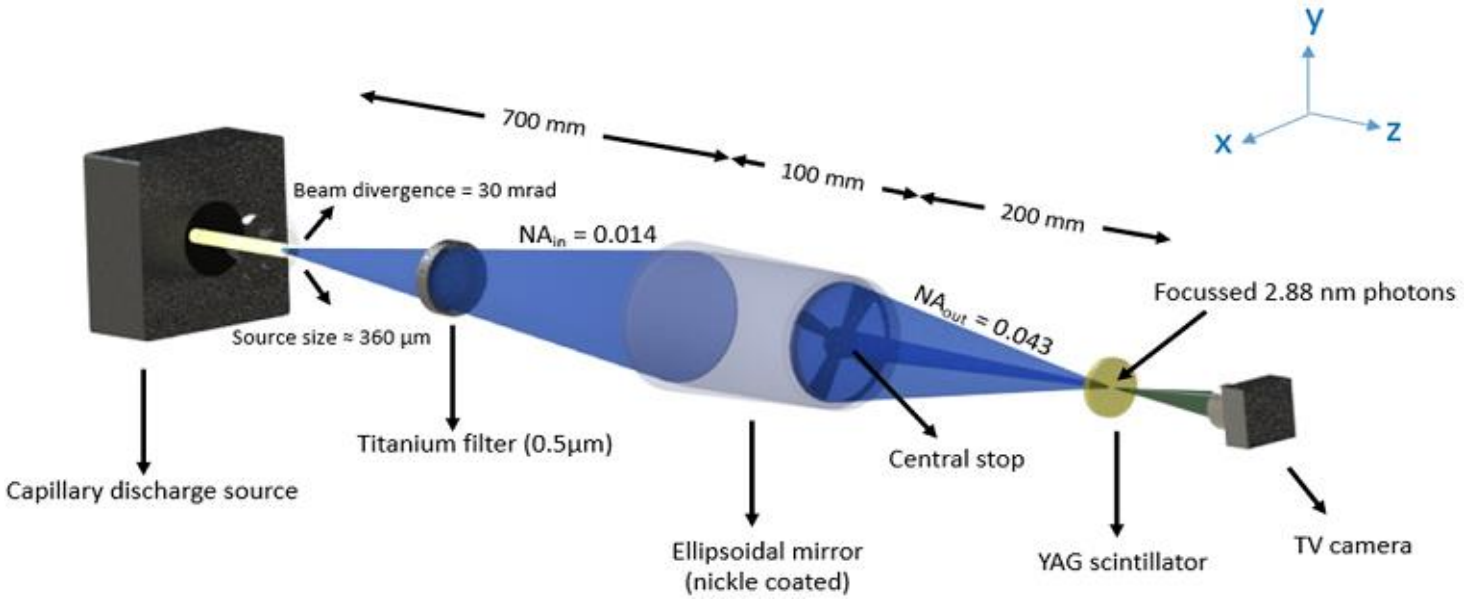


5.5×10^{13} Photons/(sr x pulse)



10^8 Photons/ (sr x pulse) in focus

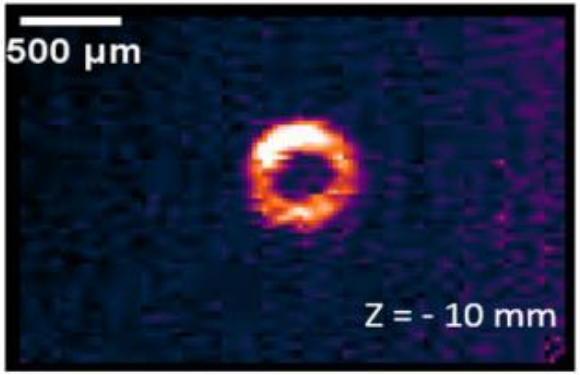
Ellipsoidal condenser mirror

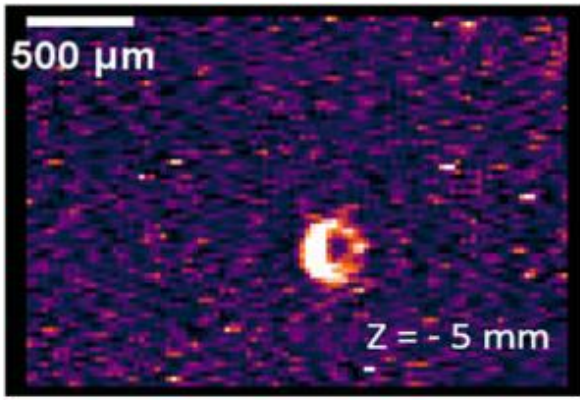


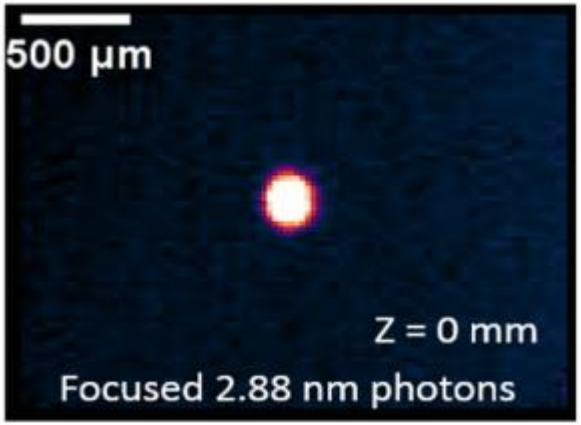
Condenser specifications	
Input numerical aperture	0.014
Output numerical aperture	0.043
Mirror length	100 mm
Type of mirror	ellipsoidal
Coated by	nickel
Focal length	200 mm

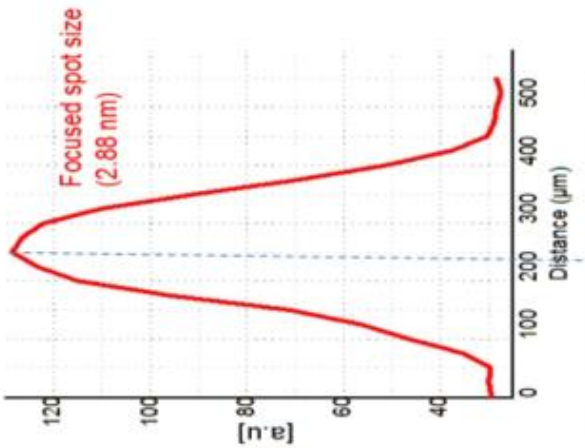
M. F. Nawaz et al.: Focusing and photon flux measurements of the 2.88 nm radiation at the sample plane of the Soft X-Ray microscope, based on capillary discharge source, *Proc. of SPIE 9510, EUV and X-ray Optics: Synergy between Laboratory and Space IV*, 951014-951014-7 (2015)

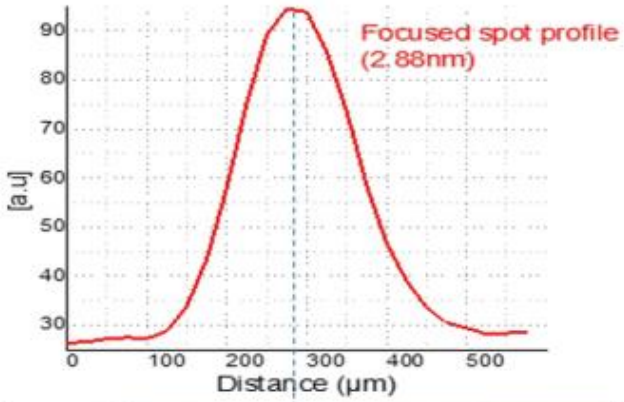
Focusing at the sample plane of SXR microscope

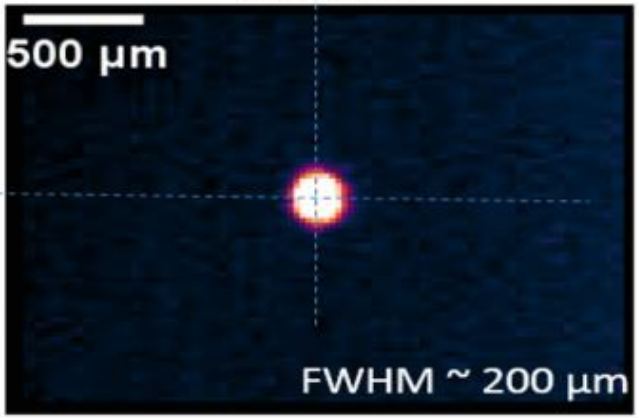






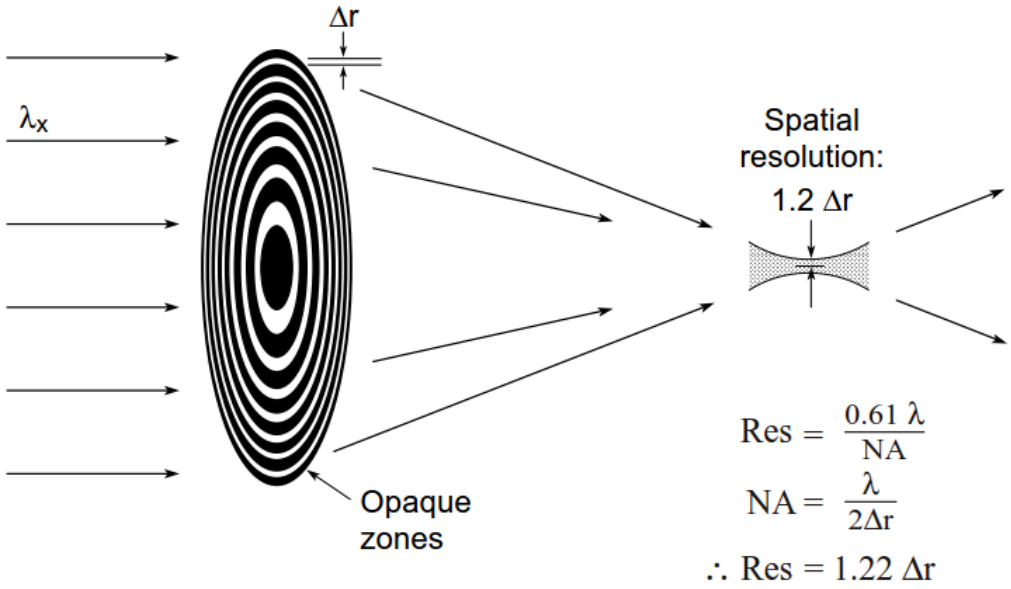


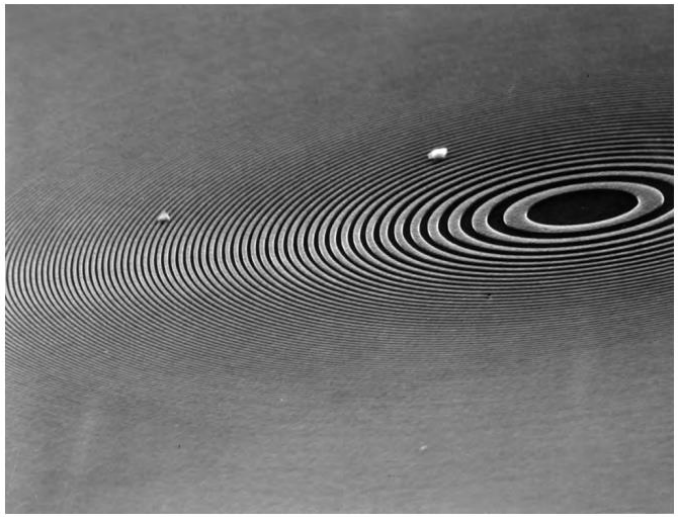




M. F. Nawaz et al.: Focusing and photon flux measurements of the 2.88 nm radiation at the sample plane of the Soft X-Ray microscope, based on capillary discharge source, *Proc. of SPIE 9510, EUV and X-ray Optics: Synergy between Laboratory and Space IV*, 951014-951014-7 (2015)

Fresnel zone plate





E. Anderson, LBNL

- Output numerical aperture of condenser is matched with numerical aperture of ZP

130 nm Tungsten on 100 nm Si_3N_4	
The width of the outer most zone (Δr)	33 nm
Numerical aperture (NA)	0.043
Total number of zones (N)	1364
Focal length (f)	2.1 mm
Diameter of the zone plate (D)	180 µm
Depth of focus	1.6 µm

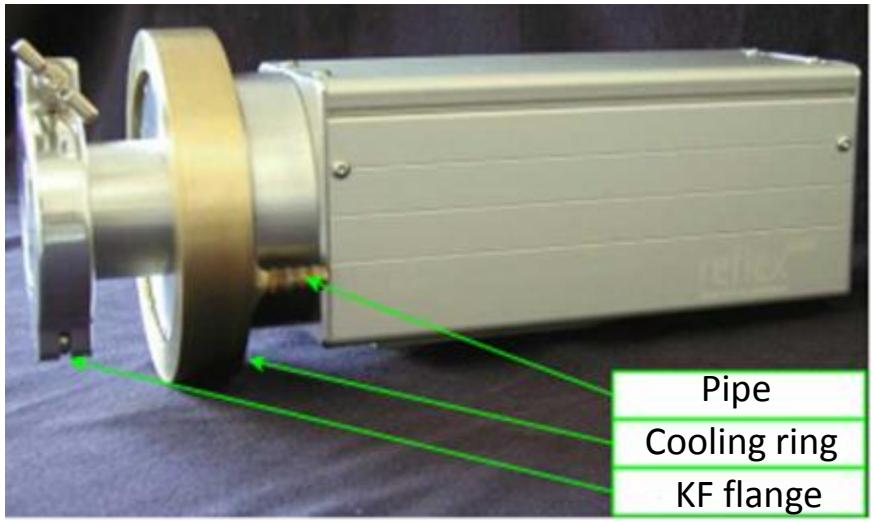
→ Rayleigh resolution = 1.22Δr ~40 nm

$\frac{\Delta\lambda}{\lambda} \leq \frac{1}{N}$ → To avoid chromatic aberration

- Diffraction efficiency in 1st order at 2.88 nm is 12 % (for Tungsten 130 nm)
- Transmission is 3.5 % at 2.88 nm

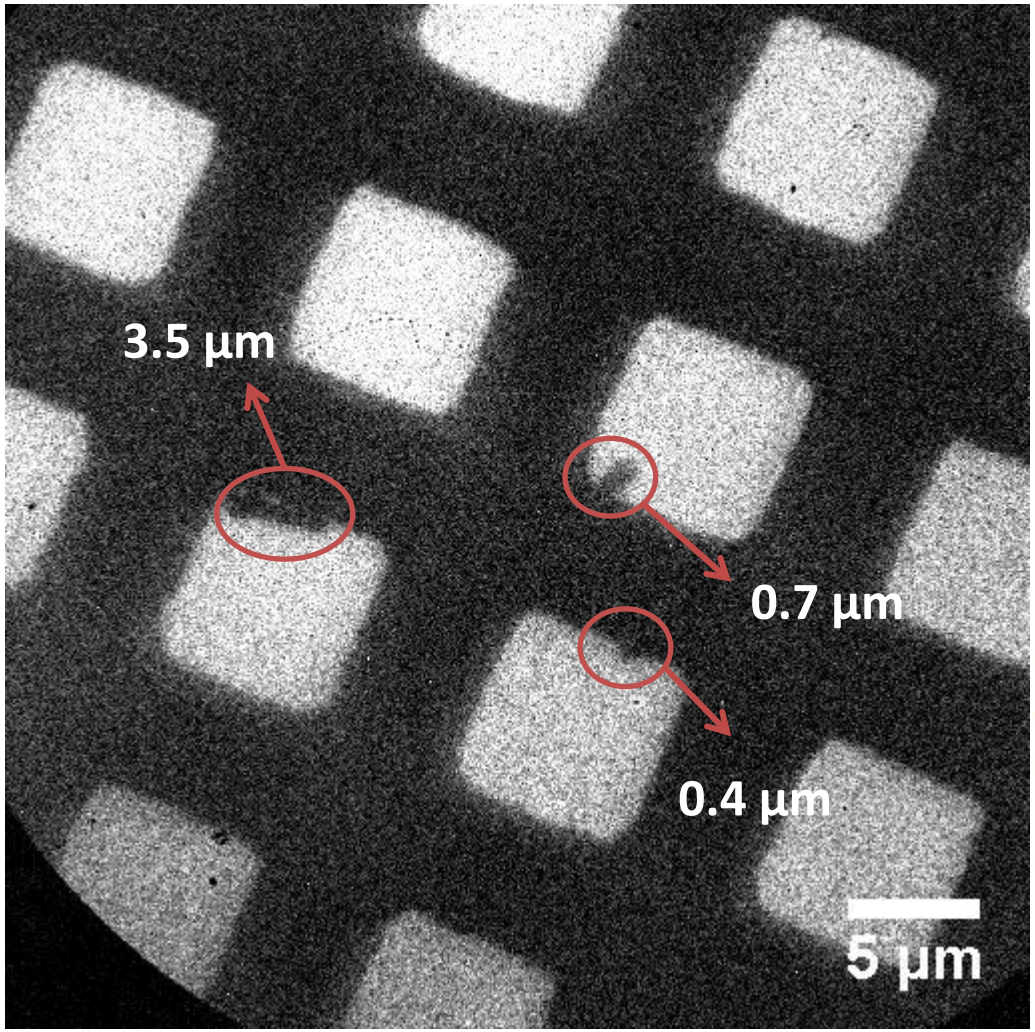
CCD camera

- Back-illuminated CCD camera
- The CCD image sensor is cooled via the Peltier element

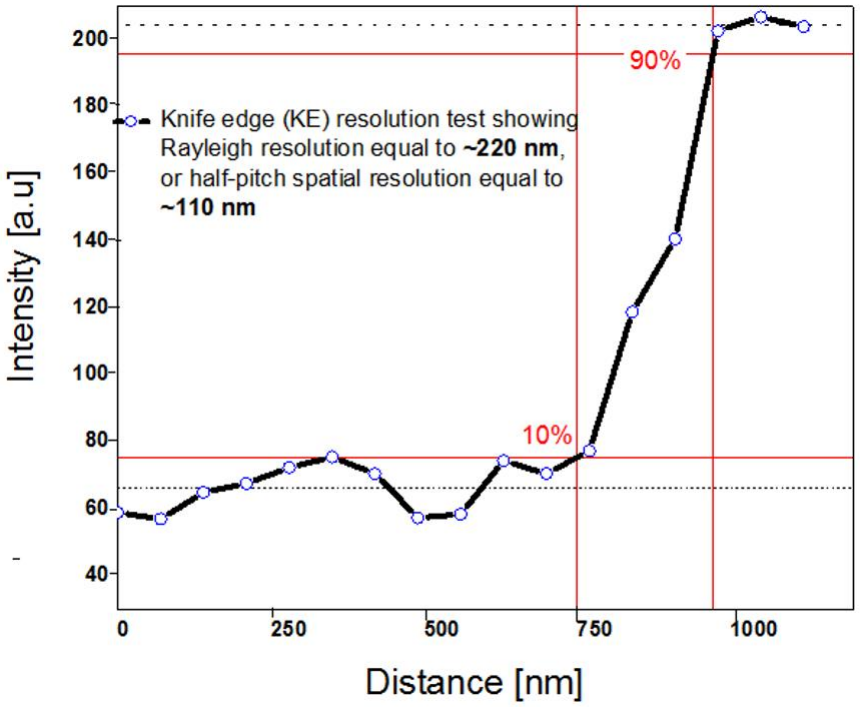


Camera specifications	X-Vision M25
Total number of pixels	512 x 512
Pixel size	24 x 24 µm
Image active area	12.3 x 12.3 mm
Exposure time	10 ms to 255 min

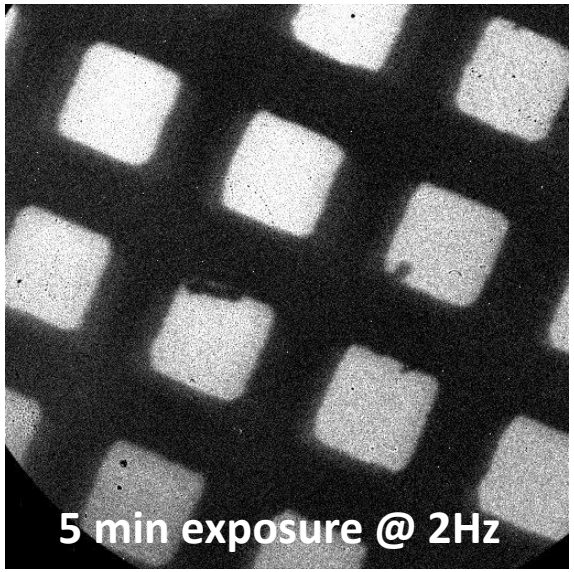
Image of Cu mesh

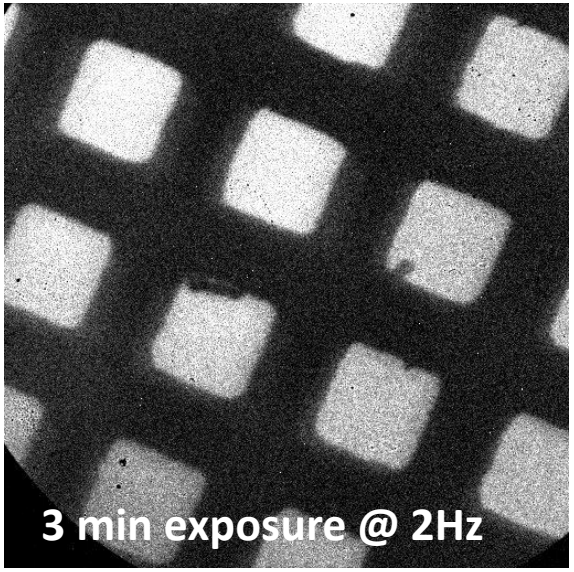


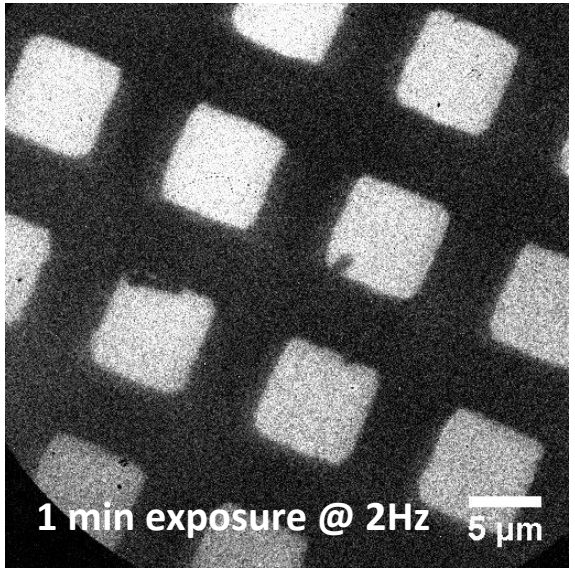
- Cu mesh with 5 µm bars and 7.5 µm holes
- Exposure time 1 min
- Repetition rate 2 Hz
- Spatial resolution 110 nm (half-pitch)
- Field of view 35 x 35 µm
- Magnification 300x

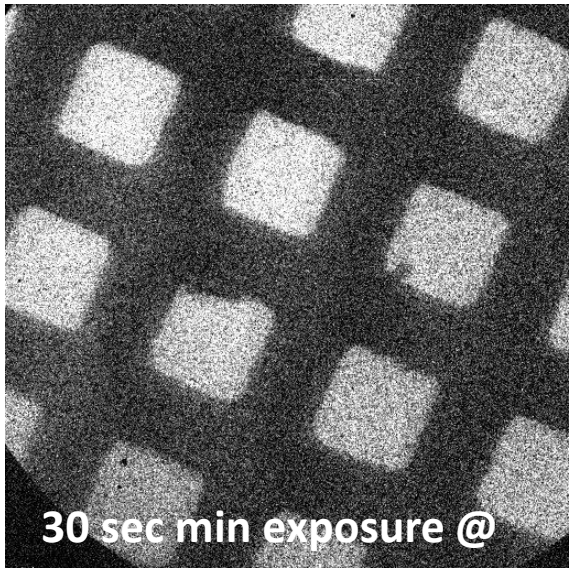


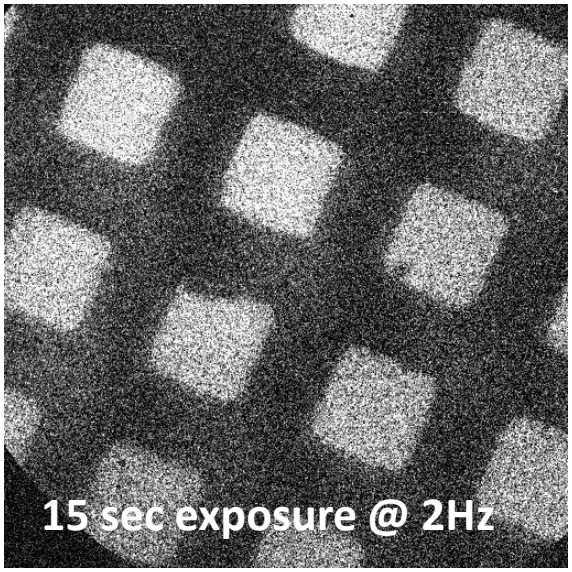
Images of Cu mesh with different exposure time

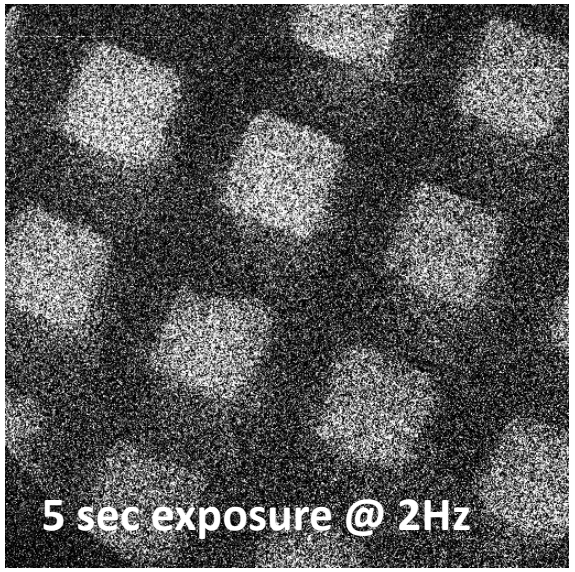




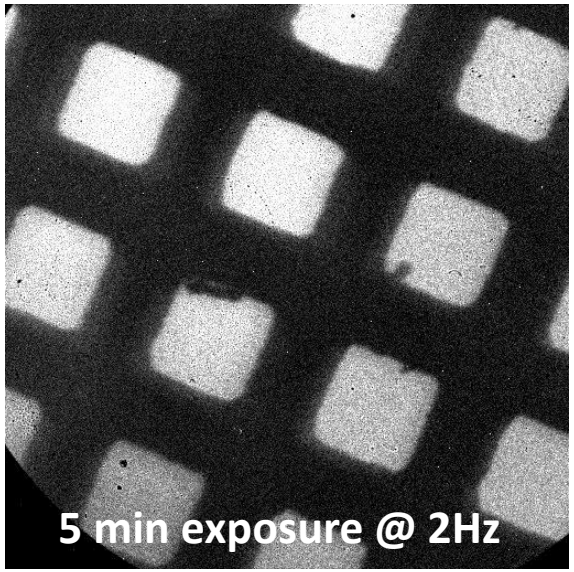


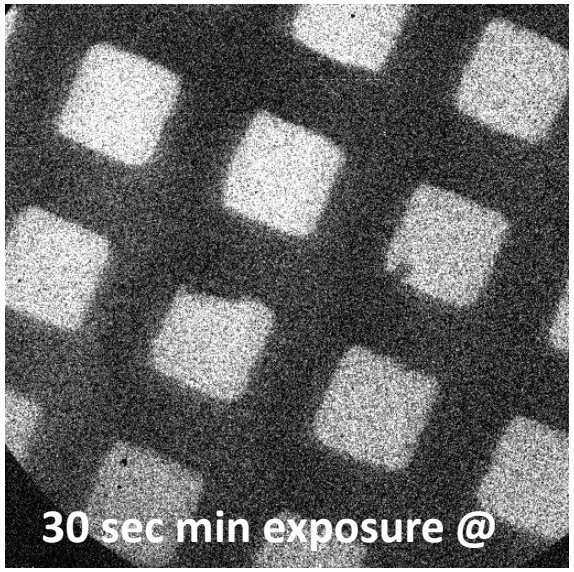


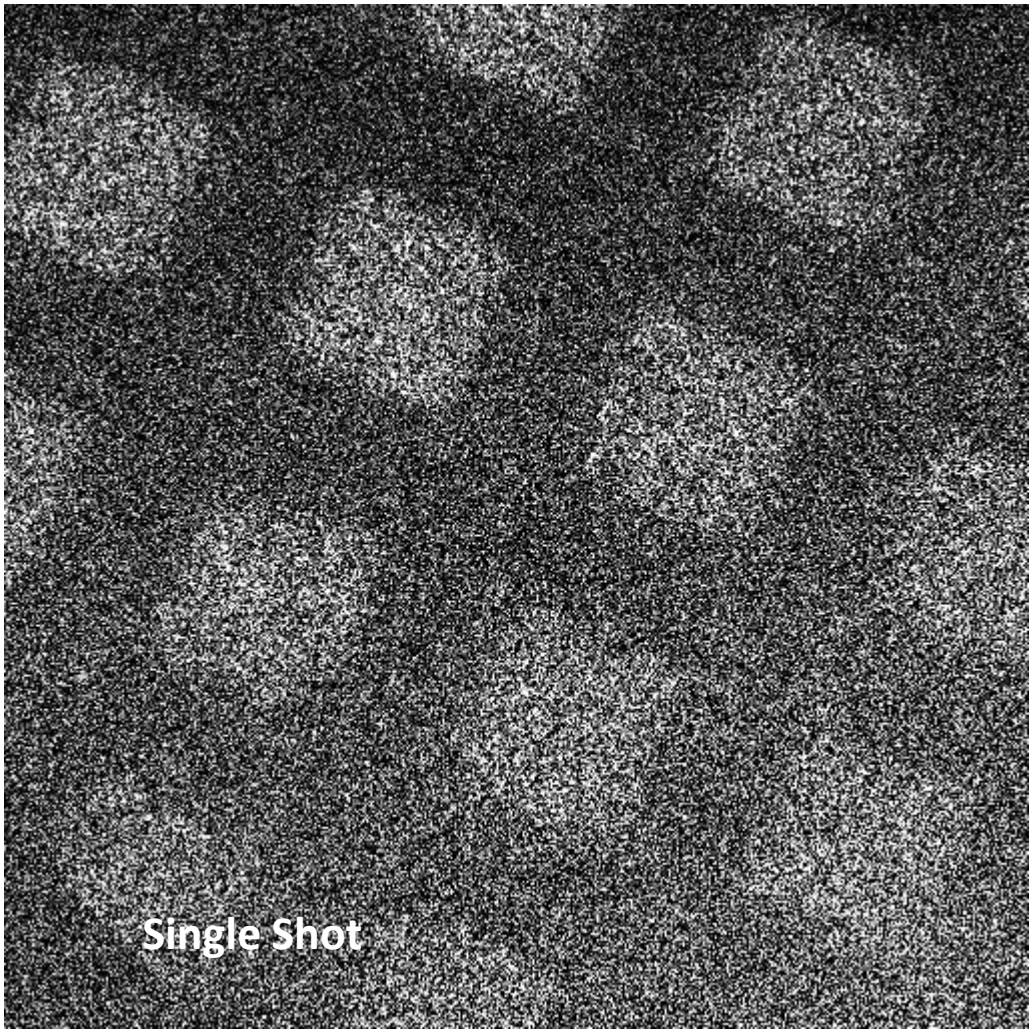




Images of Cu mesh with different exposure time







Summary and Outlook

Summary

- Pinching capillary discharge has been proved as an efficient source for SXR imaging
- Water-window microscope based on nitrogen plasma capillary discharge source has been developed
- Initial results of imaging have been demonstrated with half-pitch spatial resolution about 110 nm

Outlook

- We plan to use a thinner Ti filter for photon flux improvement
- Currently, the biological samples are under investigation
- For better SXR imaging we foresee to implement a CCD camera with higher number of pixels

Acknowledgement

Thank you for your attention

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